

DETERMINING MODEM PERFORMANCE IN THE PRESENCE OF NOISE

Noise on data communication circuits causes errors. A modem's ability to tolerate this noise is an important measure of its performance.

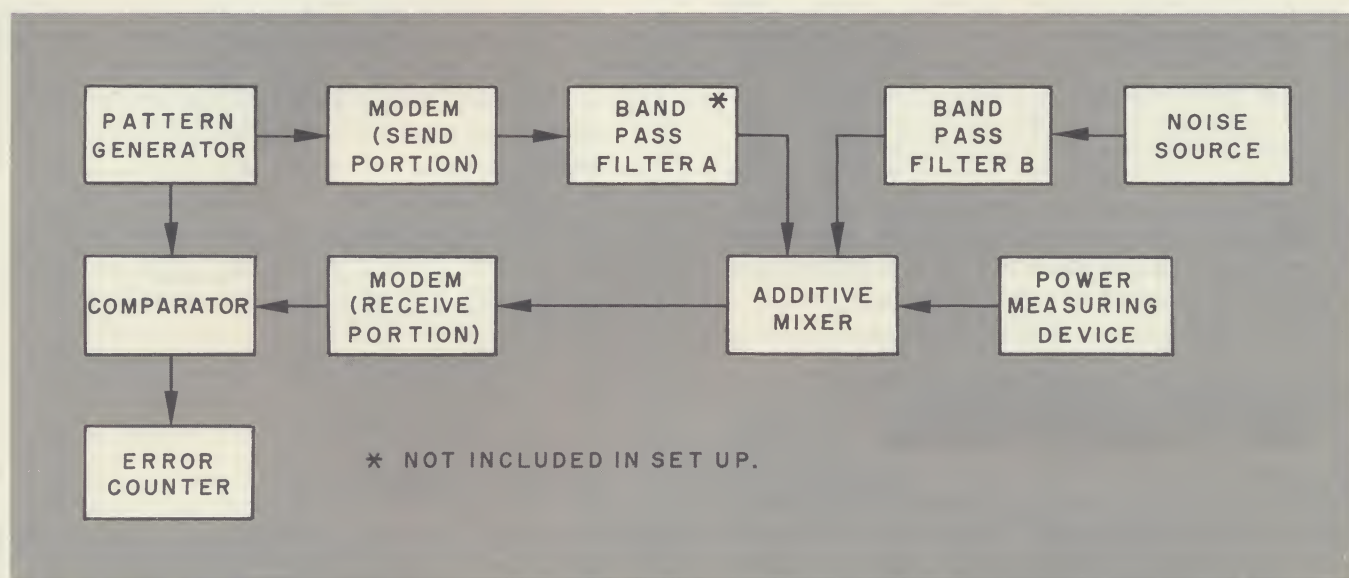


Figure 1. Block diagram of signal to noise test set-up

INTRODUCTION

This bulletin is concerned with the testing of modems to measure their performance in the presence of communications circuit noise. The types of noise, a test set-up, and the bit error rate as a performance measure are discussed. This bulletin will help the engineer understand, correlate, and use published data on modem performance relative to noise.

NOISE ON PHONE LINES

Basically two types of noise are found on phone lines — white gaussian noise and impulse noise. White gaussian noise is essentially a steady background noise which results from thermal activity of molecules in the lines, amplifiers, and other components of the phone lines. Impulse noise is usually caused by switching circuits, storms, and coupled transients from a variety of sources.

The specification for AT&T telephone circuits limits white gaussian noise to "48 dba (2B-F1A)." This may be translated to mean -37 dbm since the reference level for F1A weighting is -85 dbm. The specification further calls for a transmission level of -8 dbm and a line-up loss of 8 db $\pm$ 1 db. The minimum signal which can be expected at the receive terminal is -17 dbm with a signal/noise ratio of 37 - 17 or 20 db. The above specification brings out several facts about noise on telephone circuits. They are:

- (1) White gaussian noise is always present on phone lines.
- (2) There is a limit to the signal level that can be transmitted over a phone line.
- (3) The minimum ratio of signal to noise (S/N) to be expected on a phone line is 20 db. (The RMS signal voltage at the receiver is at least 10 times the RMS noise voltage.)

If the signal voltage is at least 10 times the noise voltage, it would seem that noise would not be a problem. This is partially true. With such a signal to noise ratio many modems can transmit 2400 bits per second with an error rate of 1 error in each 10 billion bits of data transmitted, or an average of 1 bit in error each 1150 hours. Other modems can transmit 4800 bits per second with an error rate of 1 error in each 100 thousand bits of data. Phone circuit noise causes varying numbers of errors depending on the amount of noise and the rate of transmission.

Now a look at impulse noise. AT&T 4A circuit specifications call for impulse noise of less than 90 hits per one-half hour above the level of 72 dbrnO. The reference point in this case is 0 dbrnO equals -90 dbm. Therefore, we can expect 90 hits above -18 dbm per one-half hour. The minimum signal at the receive terminal is -17 dbm as discussed earlier, giving a signal to noise rate of 1 db or less. However, no information is given on the pulse width or distribution of amplitudes above this level. These important characteristics of the impulse are required in order to determine the error rate due to impulse noise. If it is assumed that an impulse will be of the proper sense to cause errors half the time, that all of the impulses are long enough and high enough, then the error rate at 2400 bits per second would be:

$$\frac{\frac{90}{2}}{2400 \times 1800} = \frac{45}{4.32 \times 10^6} \approx 1 \times 10^{-5}$$

Rixon's experience during the past several years indicates that such a high error rate due to impulse noise is not found. It is considered that the above figure of 1 error in 10^5 bits does not represent the true effect of impulse noise.

Impulse noise does occur on phone lines but insufficient information exists to permit the construction of an impulse noise simulator for testing modems. It has been observed however that the relative performance of modems in the presence of impulse noise is the same as that for white gaussian noise.¹

The results obtained will be a valid indication of performance in the presence of both white and impulse noise.

TESTING MODEMS IN PRESENCE OF WHITE NOISE

Figure 1 shows a generalized block diagram for a test set-up for measuring modem performance in the presence of white gaussian noise. Beginning at the upper left hand portion of Figure 1, a pattern generator is used to simulate a digital data source. The pattern generator sends a digital data stream to the send portion of the modem where it is conditioned as though it is going to be sent over telephone channels.

1. The Bell System Technical Journal, October, 1965, "Digital Transmission in the Presence of Impulsive Noise" J. S. Engel

Ideally, the spectrum of the modem output signal should be limited to the frequency band of the line. However, filters are not available which would limit the transmit spectrum without distorting the phase. Therefore, the assumption is made that the modem spectrum does not contain energy outside the normal bandpass of the line and we do not include bandpass filter A in the test set-up.

A noise source is selected which produces white gaussian noise. The noise is bandlimited by bandpass filter B to assure that the noise power added to the signal is constrained to the band of interest.

The noise and the send signal are added together in the mixer. A power meter is used at the output of a mixer to measure the signal to noise ratio.

The mixed signal is transmitted to the modem receive portion where the digital data stream is recovered. The comparator compares the received digital data with the output of the pattern generator. When the received bit does not agree with that which was sent, then the comparator generates an error pulse. The errors are recorded by the counter. The tests are run at various signal to noise ratios and the error count is noted for each one.

Knowing the bit rate of the data, the duration of the test, and number of errors, the bit error rate can be calculated thus:

$$\text{Bit error rate} = \frac{N}{B \cdot D}$$

where N = number of errors

B = bit rate of the pattern generator
in bits per second

D = duration of test in seconds

NOISE SOURCES

White gaussian noise is characterized by its distribution of instantaneous voltages and spectral density. The former follows the gaussian law which states that the probability density function P(E) is defined as:

$$P(E) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(E - E_0)^2}{2\sigma^2}}$$

where E_0 = the average voltage

σ = rms voltage

This distribution is illustrated in Figure 2. The spectral density is said to be white when it is constant with frequency as illustrated in Figure 3.

Thermal noise is in general white gaussian noise with E_0 (average value) equal to zero. When this signal is added to the transmitted signal, it is called additive white gaussian noise. This is essentially what happens on a telephone line. Because the gaussian distribution predicts the presence of very high amplitudes for a finite amount of time, and if this noise signal is of the opposite sense from the transmitted signal, then the received signal is in error.

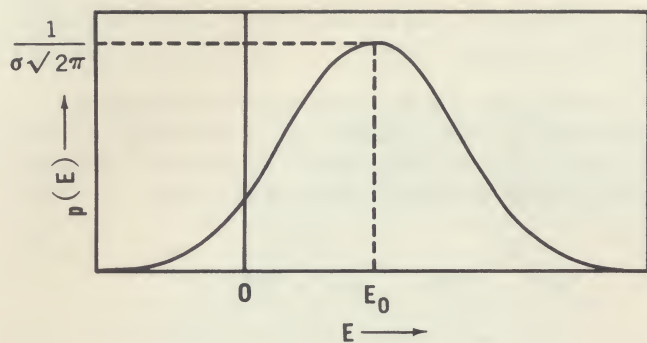
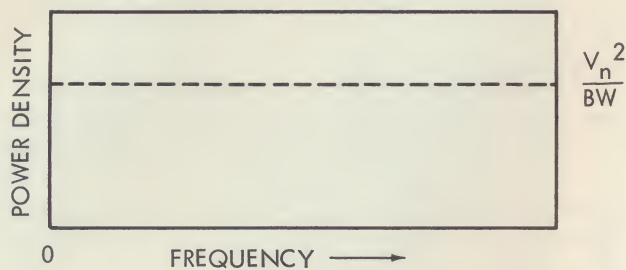


Figure 2. Gaussian probability density function.



Where V_n = Noise Voltage (Volts VMS)
 BW = Bandwidth (Hertz)
 Resistance is 1 ohm

Figure 3. White frequency spectrum.

Random noise sources are readily available which are sufficiently close to being white and gaussian that a measure of noise power in a known band completely determines the noise density across the band. Most manufacturers of noise sources publish curves to illustrate how closely their device approximates ideal white gaussian noise.

The maximum noise peaks that the noise sources can produce are limited due to the amplifiers in the path. It has been observed in the testing of modems that, below bit error rates of 1 in 10^7 , the measured curves cross over the theoretically predicted value. This indicates that the noise source is no longer producing noise peaks large enough to cause bit errors.

Noise sources are available which give good results at bit error rates above 1 in 10^7 . An example is the General Radio Type 1390-B.

NOISE FILTER

It is important that the filter does not clip the peaks. A passive filter would be ideal. But usually tunable active filters are more readily available. As long as the device is linear in amplitude response beyond the level of 5 times the maximum rms noise voltage it is usable. An example of a device which has given good results in the past is the

Krohn-Hite variable bandpass filter Model 310C. This device has a 24 db per octave attenuation outside the band. Calculations have shown that such a device has an effective noise bandwidth which is 1.03 times the 3 db setting. This has negligible effect on the noise power measurement (about 0.1 db).

It is important that the noise bandwidth be wide enough to completely encompass the passband of the phone line to be used. It is currently the practice to set the bandpass at 300 to 3000 Hertz. Many recent modem comparisons have been run using this bandwidth. The 6 db bandwidth of the schedule 4 phone lines are:

4-A	300 to 2700 Hertz
4-B	300 to 3000 Hertz
4-C	300 to 3200 Hertz

Because of the bandpass of the 4-C line has significant energy out to 3200 Hertz, it is recommended that when evaluating modems for use on 4-C line the noise bandwidth be set from 300 to 3200 Hertz. For all others, the noise bandwidth of 300 to 3000 Hertz is adequate.

MIXER

The mixer is usually a resistor network which properly terminates the modem (send portion) and the noise filter. Proper termination of these devices assures that there is no distortion of their spectrum. In addition, the mixer should provide for the separate measurement of the signal and the noise without disturbing the loading of either device.

POWER MEASURING DEVICE

Many voltmeters exist which are capable of measuring true rms. These devices are delicate, expensive, and not normally found in test equipment rooms. More readily available, however, are vacuum tube voltmeters such as the Ballentine 310-A or the Hewlett Packard 400-H. These instruments are intended to measure rms voltage of sine waves. The meter movement reads the average value of the input signal and the scale is calibrated to read rms. When these meters are used to measure noise, they do not indicate true rms of the noise. Theoretically, they read 1.04 db low. Comparison measurements of the General Radio 1390-B using the vacuum tube voltmeters described above and a true rms voltmeter indicates a difference of 0.96 db. The difference between the theoretical value and the measured value ($1.04 - 0.96 = 0.08$ db) is attributed to instrument tolerance.

In any event, when making comparative tests of modems the inaccuracy of measuring noise with a vacuum tube voltmeter is applied to all modems equally. When comparing published data on modem error rate, the reader seldom knows what type meter was used and there is a margin of uncertainty of approximately 1 db.

PATTERN GENERATOR

A pattern generator is used to generate a series of bits to simulate a digital data stream. The theoretical error probability prediction is valid for any pattern. However, in the general case the modem is pattern sensitive and will perform differently for different patterns.

This is the result of practical aspects of the modem such as its modulation scheme, automatic gain control implementation, and clock recovery technique.

Most recent comparison tests of modems have been made using pseudo-random pattern generators. The advantages of these generators are that: (1) they spread out the modem signal spectrum over the band of interest, revealing any weakness the modem has to any particular part of the spectrum. (2) While generating the random bit stream, it generates all patterns possible to some maximum length N .

For example, when using a pseudo-random pattern generator which repeats every 511 bits, all possible combinations of 9 bit sequences are generated. The value $N = 9$ is determined from the relationship $2^N - 1 = 511$. At Rixon a pseudo-random generator of length 32,732 is used which generates all possible 15 bit sequences. The pseudo-random generator has the advantage over short patterns of 8, 16, or 32 in that it exercises the modem in all patterns.

When a modem is used to transmit computer data, the character length is usually known. If the computer has an eight bit character length, then testing with a pseudo-random pattern generator of length 255 or greater exercises the modem for all possible characters. To accomplish the same thing with an eight bit pattern generator would require that the error rate test be run for each sequence of eight bits or 256 runs.

Another type of pattern sensitivity which modems exhibit is a sensitivity to a long sequence of all ones or all zeros. Most modems require some data transitions to recover clock for their detection scheme. Long sequences of all ones or all zeros deny the modem these transitions and its ability to recover data suffers. The errors usually occur in the bits following the stream of ones or zeros. If the data system engineer expects this situation to occur, he should discuss this problem with the modem manufacturer.

One solution to this problem is the use of code converters. Code converters can be designed to detect long sequences of ones and zeros and cause periodic transitions. At the receive end, a complimentary code converter restores the data sequence to its original state.

It is recommended that error rate measurements be taken using a pseudo-random pattern generator. Most recent comparisons have been performed with a 511 bit or greater pseudo-random pattern generator. In addition, the error rate measurements should be taken under conditions of any repetitive pattern which is anticipated. For example, if all zeros or all ones are sent when no data is being sent, the modem should be tested for this case. If code converters are used they should be considered as part of the modem.

USING THE TEST SET-UP

Typical results are shown in Figure 4. The solid line represents the theoretical performance for the modulation method used. The black dots represent measured data. Notice that both the bit rate (2400) and the noise bandwidth (f_n) are clearly labeled. A higher bit rate would move the curve to the right. A larger noise band-

width (f_n) would move the curve to the left. The reason for this is discussed later.

Note that the data is not taken at the expected S/N of 20 db. The reason for this is that the duration of test required is unreasonable. For example: to obtain 1 error in 10^7 at 2400 bits per second required

$$\frac{10^7}{2400 \times 3600} = \frac{10^7}{8.6 \times 10^6} = 1 \text{ hr.}$$

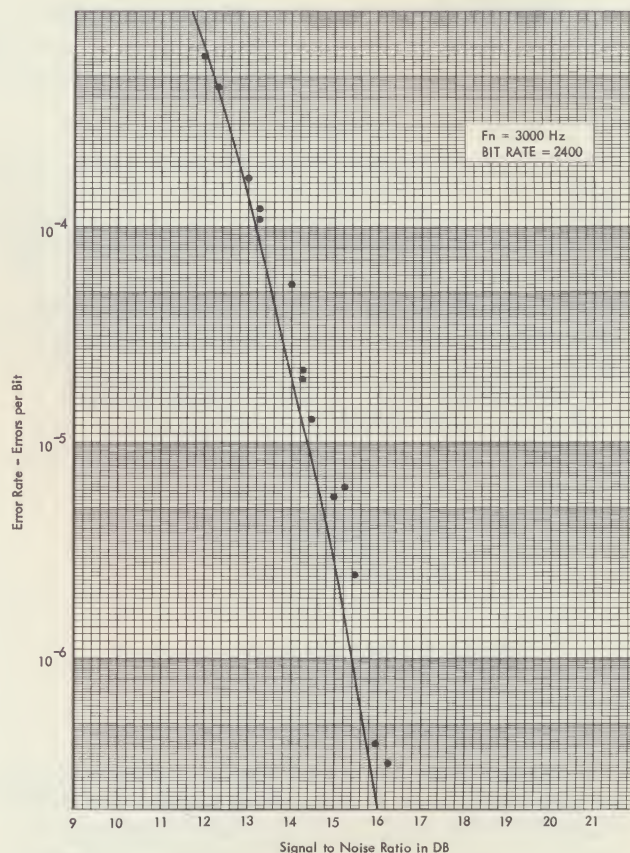


Figure 4. Typical Error Rate Curve

Obtaining a reasonable number of errors for good statistical confidence requires considerable time; for example 20 errors requires 20 hours.

For this reason most data is taken and results reported at error rates of 1 in 10^6 or greater. By comparing modem performance at this point, we can extrapolate the expected performance at 20 db. Typically, the error rate curve for a modem which is performing according to theory has a slope of approximately 1 decade per 1 db. Therefore, a modem with a bit error rate of 1 in 10^5 at 15 db S/N would have a bit error rate of approximately 1 in 10^{10} at 20 db.

It is these points that are of interest to the potential user. Using measured data for various equipments, he can make a qualitative comparison and select the one suitable for his use. The only way to assure that data is comparable for various equipments, is to test the equipment under consideration using the same conditions.

ESSENTIALS OF BIT ERROR RATE PRESENTATION

Users who employ a large number of data modems can run comparison tests to evaluate the relative performance of modems. The data systems engineer who is buying or leasing only a few modems cannot afford to run these tests and must rely on the manufacturers data to select his modem.

A typical performance claim for a modem is "Bit error rate less than 1 in 10^5 at 2400 bits per second on a schedule 4A line with S/N of 15 db." This represents an extrapolation from the data obtained by the tests we have just described and is subject to the manufacturers interpretation of the other impairments to data transmission. These claims can only be verified by actual operation of the modem over an extended period of time.

A more valid comparison of modem performance in the presence of noise can be obtained by comparing error rate curves as shown in Figure 4. The problem with comparing such curves is a lack of standardization in the testing and presentation of data.

The following paragraphs are devoted to showing correction factors which may be used so that error rate curves from various manufacturers can be compared.

The generalized expression for error probability in the presence of noise is:²

$$P = \frac{1}{2} \left[1 - \operatorname{erf} x \right] \quad (1)$$

$$X = \frac{V_s}{V_n} \sqrt{\frac{F_n}{b}} \frac{1}{\sqrt{2}} \quad (2)$$

where V_s = signal voltage (volts vms)
 V_n = noise voltage (volts vms)
 F_n = noise bandwidth (hertz)
 b = bit rate (bits per second)

It can be seen from equations (1) and (2) that the error rate is a function of V_s/V_n (the signal to noise ratio), F_n (noise bandwidth) and b (bit rate). When an error rate curve is labeled with these parameters, then it can be compared to another error rate curve which is similarly labeled.

Figures 4 and 5 are properly labeled error rate curves. The solid line of Figure 4 is the predicted bit error rate for the modem based on equations 1 and 2 with the signal to noise ratio modified to account for the part of the signal which is devoted to carrier. (In this case the line is moved 3 db to the right because 100% VSB modulation is used.)

Figure 5 shows an actual error rate curve for the Rixon 4 phase modem — the PM 24 data set. The points given were results taken using a test set-up like Figure 1.

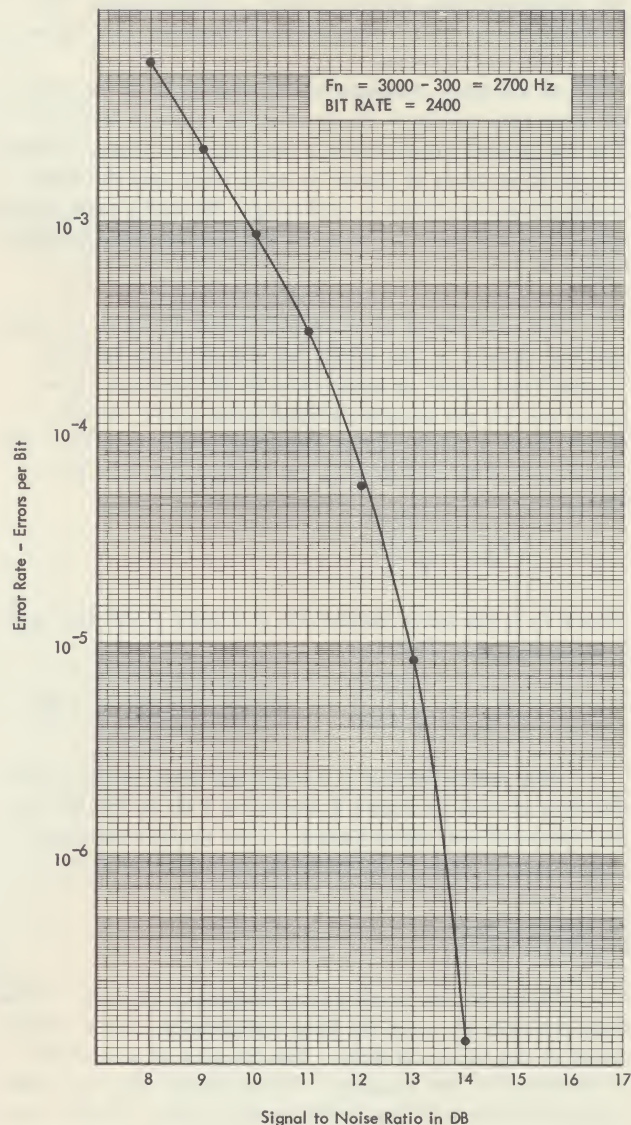


Figure 5. Error Rate Results for PM 24 Data Set

If the curve of Figure 4 is to be compared to the curve of Figure 5, then the difference in the noise bandwidths must be considered.

To make a valid comparison between two bit error rate curves obtained with different noise bandwidths the result of one curve must be modified by a factor of:

$$F_1 = \sqrt{\frac{F_{n1}}{F_{n2}}}$$

where F_{n1} = the noise bandwidth of the curve being modified (hertz)

F_{n2} = the noise bandwidth of the reference curve (hertz)

For the example:

$$F_1 = \sqrt{\frac{3000}{2700}} = \sqrt{1.11} = 1.053 = 0.46 \text{ db}$$

The curve with the 3000 Hertz noise bandwidth looks .46 db better than the one with $F_n = 2700$ Hertz. The effect of F_n on error rate curves is illustrated in Figure 6.

In the past, attempts have been made at labeling bit error rate curves in terms of noise spectral density. This has proved unsatisfactory because line characteristics are given in terms of signal to noise ratio and the more academic presentation is confusing. Recently most modem manufacturers have switched to the form as illustrated by Figure 4.

An example of an error rate curve in terms of noise spectral density is one which has the abscissa labeled "normalized signal to noise ratio in db (average signal power per bit per second divided noise power density in db)." Such a curve can be denormalized into S/N in db like Figure 4 by multiplying the normalized S/N by a factor

$$F_2 = \sqrt{\frac{f_n}{b}}$$

Where f_n is the noise bandwidth of Figure 4 (3K Hz) and b is the bit rate (2400 bps).

$$F_2 = \sqrt{\frac{3000}{2400}} = \sqrt{1.25} = 1.12 = 1 \text{ db}$$

This indicates that a normalized error rate curve for the data plotted in figure 4 would be 1 db to the left of the denormalized curve shown. (The normalized curve would appear to be 1 db better in performance.)

SUMMARY

Noise occurs in all voice frequency circuits. When these circuits are used for data transmission, noise causes errors in the received data. The measure of a modem's performance in the presence of noise is the bit error rate and is a function of the signal to noise ratio. When comparing data for different modems, it is important to assure that the equipment being considered has been tested under the same conditions. If not, the data can be corrected as described in this bulletin.

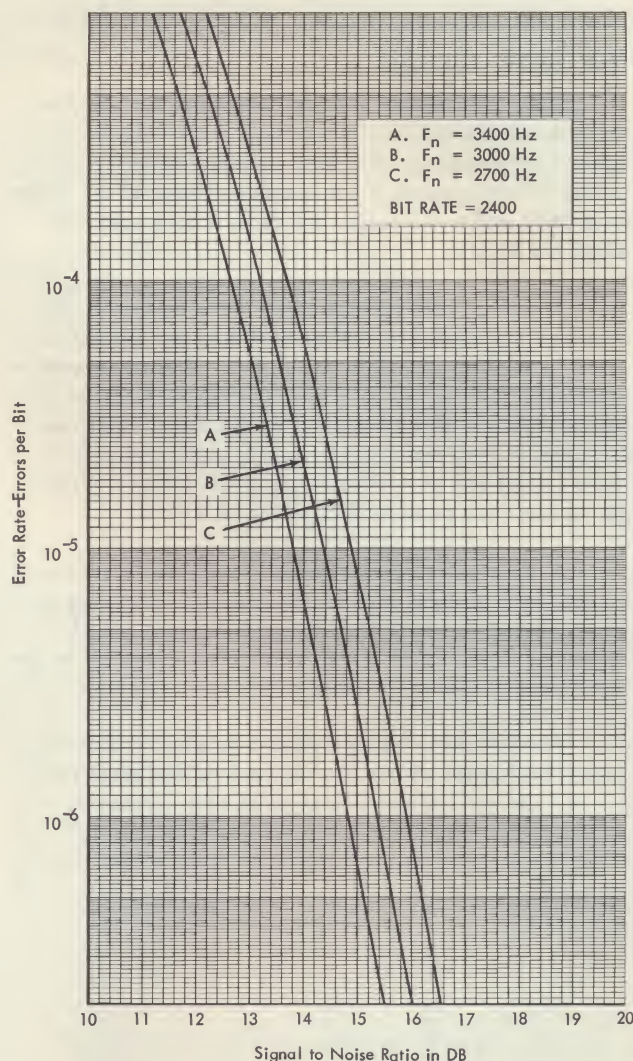


Figure 6. Effect of Noise Bandwidth on Error Rate